AUG 1 6 1988

A 13.78: NC-282

United States
Department of
Agriculture

Forest
Service

North Central
Forest Experiment
Station

Research
Paper NC-282

# Nutrient Accumulation in Planted Red and Jack Pine

David H. Alban

BEST COPY AVAILABLE

COMPLETED

ORIGINAL

Allen, David H.
1988. Nutrient accumulation in planted red and jack pine. Res. Pap. NC-282. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 6 p.

Compares nutrient accumulation in adjacent plantations of red and jack pine in the upper Great Lakes. Describes equations developed to predict biomass and nutient accumulation based on stand basal area and height.

KEY WORDS: *Pinus banksiana*, *Pinus resinosa*, nitrogen, phosphorus, potassium, calcium, magnesium, upper Great Lakes.

**North Central Forest Experiment Station**
**Forest Service—U.S. Department of Agriculture**
**1992 Folwell Avenue**
**St. Paul, Minnesota 55108**
**Manuscript approved for publication February 12, 1988**
**1988**

# NUTRIENT ACCUMULATION IN PLANTED RED AND JACK PINE

David H. Alban

As forest management intensifies, rotations are usually shortened, trees are more completely utilized, and nutrient removals from a site are increased. The possibility of lowering site productivity through nutrient removals in timber harvesting is an increasing concern as forest management has intensified (Freedman 1981, Gessel 1986, Leaf 1979, Turvey 1981). Both red pine (*Pinus resinosa* Ait.) and jack pine (*Pinus banksiana* Lamb.) can produce high yields under plantation management (Benzie 1977a,b; Lundgren 1983). Red pine, in particular, yields more than its most common associates under a range of site conditions (Alban 1985). Because red pine and jack pine are most commonly found on sandy, nutrient poor soils, the possibility for site degradation through nutrient loss is perhaps greater for these species than for others.

Rational decisions concerning nutrient management and long-term site productivity require knowledge of the nutrient content of forest stands and the amount of nutrients removed under various harvesting options. Few data are available on nutrient accumulation in red and jack pine plantations in the upper Great Lakes. Bockheim *et al.* (1986) reported nutrient accumulation in a red pine plantation in Wisconsin, and Perala and Alban (1982) documented nutrient accumulation in red and jack pine on two sites in Minnesota. Green and Grigal (1980) reported nutrient accumulation in natural stands of jack pine more than 50 years old from a restricted area of northeastern Minnesota.

In other geographic regions, Foster and Morrison (1976) examined nutrient accumulation in three natural jack pine stands in northern Ontario. Wittwer *et al.* (1975) determined nutrients in plantation red pine on potassium-deficient sites in New York. The applicability of these results to the upper Great Lakes is unknown.

**DAVID H. ALBAN** is a Research Soil Scientist with the North Central Forest Experiment Station, Grand Rapids, Minnesota.

The purposes of this paper are to compare the nutrient accumulation in adjacent plantations of red and jack pine, and to develop models to predict nutrient content in these species as functions of easily measured stand variables.

## METHODS

We sampled 24 stands of adjacent red and jack pine plantations scattered throughout the upper Great Lakes and ranging from 19 to 46 years in age (table 1). The sites represent a wide range of soils (although most are sandy) and nearly the complete range of site index for these species. None of the stands had been thinned.

In most cases the adjacent red and jack pine plantations were established the same year. For three stands, the ages for the two species differed (2, 3, and 5 years). For these stands the basal area (B) and height of dominant and codominant trees (H) of red pine were adjusted to the age of the jack pine stands. The B adjustment was made by the program REDPINE (Lundgren 1981), and the H adjustment was made from the site index equations for red pine (Lundgren and Dolid 1970). After this small adjustment, red and jack pine growth on each of the 24 adjacent stands could be compared directly.

At each site, soil borings were made to ensure that the adjacent plantations had been established on the same soil. Soils on each area were described and classified by National Forest or by Soil Conservation Service soil scientists. At each site, three 0.04 ha plots were established in both the red pine and the jack pine. On each plot the diameter (d.b.h.) of every tree was measured, and height was measured on 10 trees representing the range of diameters. Mean tree diameter and a height diameter curve were calculated in the field. On each plot, one tree of mean bole volume was felled. Most of these trees were in the codominant crown class, as are most trees in the plantations sampled.

For each sample tree, the limbs and 1-meter bolts from the bole were removed and weighed in the

Table 1.—Mean stand and site characteristics

| | Stand age (Years) | Red pine | | Jack pine | | Location | Soil |
|---|---|---|---|---|---|---|---|
| | | Basal area | Site index | Basal area | Site index | | |
| | | $m^2/ha$ | $m$ | $m^2/ha$ | $m$ | | |
| | 19 | 20.3 | 18.6 | 20.7 | 19.5 | Minnesota | Menahga |
| | 25 | 37.4 | 20.8 | 30.2 | 22.1 | Minnesota | Zimmerman |
| | 26 | 31.7 | 19.8 | 29.5 | 22.3 | Minnesota | Unnamed |
| | 30 | 50.1 | 22.3 | 37.1 | 21.0 | Minnesota | Redby |
| | 32 | 41.6 | 17.4 | 25.0 | 17.1 | Wisconsin | Plainfield |
| | 32 | 36.2 | 16.4 | 20.0 | 13.0 | Upper Michigan | Grayling |
| | 32 | 49.8 | 21.2 | 32.2 | 23.1 | Upper Michigan | Rubicon |
| | 32 | 44.9 | 19.8 | 32.5 | 21.5 | Upper Michigan | Rubicon |
| | 32 | 35.0 | 12.6 | 24.9 | 13.9 | Lower Michigan | Grayling |
| | 33 | 50.4 | 23.5 | 25.6 | 20.5 | Lower Michigan | Graycalm |
| | 34 | 39.0 | 16.3 | 28.2 | 18.8 | Upper Michigan | Rubicon |
| | 34 | 49.2 | 22.5 | 35.9 | 23.7 | Minnesota | Unnamed |
| | 34 | 51.8 | 21.7 | 33.4 | 24.2 | Minnesota | Itasca |
| | 35 | 36.5 | 15.7 | 22.9 | 14.8 | Lower Michigan | Grayling |
| | 35 | 54.7 | 20.0 | 21.9 | 18.1 | Lower Michigan | Croswell |
| | 35 | 36.4 | 19.0 | 22.2 | 17.6 | Wisconsin | Vilas |
| | 36 | 26.9 | 13.3 | 15.9 | 12.4 | Lower Michigan | Grayling |
| | 36 | 46.1 | 21.2 | 31.5 | 21.7 | Upper Michigan | Kalkaska |
| | 36 | 39.4 | 20.5 | 30.5 | 22.6 | Wisconsin | Vilas |
| | 39 | 49.5 | 22.0 | 26.8 | 21.9 | Wisconsin | Padus |
| | 39 | 51.9 | 20.7 | 35.1 | 21.0 | Minnesota | Warba |
| | 41 | 49.3 | 19.3 | 30.4 | 21.9 | Minnesota | Cutaway |
| | 46 | 57.2 | 18.9 | 25.2 | 18.7 | Lower Michigan | Grattan |
| | 46 | 61.5 | 21.1 | 30.3 | 19.3 | Lower Michigan | Kalkaska |
| Mean | 34 | 44 | 19.4 | 28 | 19.6 | | |
| Range | 19-46 | 20-62 | 13-24 | 16-37 | 12-24 | | |

field. Subsamples of the limbs and discs from the bolts were sealed in plastic bags and taken to the laboratory for separation of foliage from limbs and bole bark from the wood. All components (foliage, live branches, dead branches, bole bark, and bole wood) were dried at 75° C to determine oven-dry weights. Nutrients in each of the components were determined by a Technicon II AutoAnalyzer[1] (nitrogen and phosphorus) or by a Perkin-Elmer 5000 Atomic Absorption spectrophotometer (calcium, magnesium, potassium).

Stand biomass and nutrient content for each plot were obtained by multiplying the biomass and nutrient content of the sample tree times the number of trees per plot. Stand tree biomass and nutrient content were calculated as the mean of the three plots per species. The biomass and nutrient content of red and jack pine in each adjacent stand were compared by analysis of variance. Statistical testing was done at the 5 percent confidence level.

Stand tree biomass and nutrient content models were developed by regressing these variables against stand basal area or basal area times height. The form of the models developed was:

$$\ln(Y) = a + b \ln(X)$$

where Y is biomass or nutrient content, X is BH or B, and a and b are the coefficient estimates.

The ln-ln model form is appropriate for most forest biomass applications, but results in a bias in the a coefficient and the standard error. Bias was corrected by the method of Baskerville (1972).

[1]Mention of trade names does not constitute endorsement by the U.S. Forest Service.

Table 2.—*Total above-ground biomass and nutrient contents for each red and jack pine stand*

| Stand age (Years) | Biomass | | N | | P | | K | | Ca | | Mg | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | RP | JP | RP | JP | RP | JP | RP | JP | RP | JP | RP | JP |
| | *t/ha* | | *kg/ha* | | | | | | | | | |
| 19 | 46 | 56 | 148 | 185 | 16.7 | 19.5 | 68 | 75 | 86 | 105 | 19.8 | 21.2 |
| 25 | 117 | 120 | 287 | 282 | 31.6 | 27.7 | 138 | 133 | 183 | 164 | 45.6 | 36.2 |
| 26 | 85 | 111 | 180 | 226 | 22.5 | 22.9 | 92 | 93 | 133 | 169 | 28.1 | 29.3 |
| 30 | 153 | 147 | 341 | 311 | 45.3 | 33.0 | 128 | 110 | 239* | 182 | 62.4* | 49.8 |
| 32 | 120* | 87 | 249 | 191 | 26.7* | 16.3 | 114* | 70 | 225* | 124 | 39.6* | 23.0 |
| 32 | 112* | 66 | 268* | 204 | 27.8* | 15.8 | 109* | 65 | 181* | 128 | 35.3* | 19.0 |
| 32 | 153 | 134 | 279* | 237 | 33.4* | 21.2 | 150* | 101 | 258* | 178 | 50.0* | 32.6 |
| 32 | 146 | 129 | 323* | 263 | 31.2* | 21.8 | 127 | 06 | 255* | 173 | 49.6* | 32.9 |
| 32 | 77 | 84 | 214 | 229 | 23.5 | 21.6 | 99 | 90 | 185 | 156 | 32.8 | 28.3 |
| 33 | 194* | 110 | 366* | 230 | 43.5* | 22.1 | 179* | 93 | 343* | 153 | 62.5* | 26.6 |
| 34 | 111 | 116 | 229 | 228 | 23.7 | 19.1 | 103 | 99 | 152 | 130 | 32.0 | 29.7 |
| 34 | 186* | 150 | 314* | 217 | 37.7* | 21.3 | 157* | 113 | 266* | 168 | 62.7* | 37.2 |
| 34 | 180 | 171 | 291 | 243 | 33.6 | 27.4 | 165 | 132 | 274 | 219 | 51.0 | 43.6 |
| 35 | 106* | 80 | 224 | 196 | 24.7* | 17.8 | 100 | 77 | 182* | 117 | 34.4* | 21.8 |
| 35 | 191* | 90 | 321* | 202 | 26.6* | 17.1 | 154* | 89 | 306* | 126 | 55.8* | 21.5 |
| 35 | 118* | 82 | 232* | 146 | 23.8* | 12.7 | 114* | 75 | 183* | 104 | 38.0* | 20.8 |
| 36 | 69* | 52 | 163* | 139 | 16.3* | 10.2 | 60* | 49 | 146* | 90 | 22.0* | 12.1 |
| 36 | 162 | 145 | 276 | 254 | 31.7* | 21.5 | 132 | 103 | 260* | 177 | 46.2* | 31.8 |
| 36 | 142 | 129 | 247* | 175 | 28.3* | 17.3 | 133* | 88 | 207* | 153 | 42.9 | 28.5 |
| 39 | 197* | 131 | 371* | 214 | 41.5* | 18.0 | 176* | 85 | 294* | 150 | 63.1* | 28.0 |
| 39 | 198* | 148 | 343* | 258 | 40.9* | 24.5 | 174* | 97 | 307* | 197 | 57.3* | 37.3 |
| 41 | 175* | 130 | 287 | 229 | 32.3* | 19.5 | 155* | 105 | 271* | 163 | 54.7* | 34.6 |
| 46 | 235* | 117 | 440* | 216 | 42.0* | 2.3 | 135* | 78 | 408* | 153 | 75.2* | 24.8 |
| 46 | 284* | 148 | 463* | 320 | 50.0* | 27.5 | 159* | 95 | 395* | 174 | 81.2* | 29.9 |
| Mean | 148 | 115 | 286 | 228 | 32.0 | 21.0 | 130 | 94 | 239 | 154 | 48.0 | 29.5 |
| Mean percent by which red pine is greater than jack pine | 29 | | 25 | | 52 | | 38 | | 55 | | 63 | |

*Significantly different from jack pine at the 5 percent confidence level

## RESULTS AND DISCUSSION

### Accumulation in Adjacent Stands

In most plantations, red pine accumulated significantly more biomass and nutrients than jack pine (table 2); and in all the other cases, the differences were not significant. In its early years, jack pine grew more rapidly than red pine (Benzie 1977a,b), but by about age 20, the accumulation of volume, biomass, or nutrients was similar for these two species. Beyond this age, red pine accumulated significantly more biomass and nutrients in nearly all of the adjacent plantations examined (table 2).

Red pine biomass averaged 29 percent greater than jack pine biomass (table 2), which is somewhat less than the 40 percent differential in boiewood volume reported previously (Alban 1978). Species differences in volume are greater than in biomass, primarily because wood density of jack pine is about 10 percent greater than that of red pine (Alban 1978).

Red pine averages 25, 52, 38, 55, and 63 percent greater accumulation than jack pine of N, P, K, Ca, and Mg, respectively (table 2). Nutrient differences between these species are (except for nitrogen) larger than biomass differences. The greater nutrient accumulation of red pine is explained part-

Table 3.—*Mean tissue nutrient concentrations in adjacent stands of red and jack pine*

| | Nitrogen | | Phosphorus | | Potassium | | Calcium | | Magnesium | |
|---|---|---|---|---|---|---|---|---|---|---|
| | RP | JP | RP | JP | RP | JP | RP | JP | RP | JP |
| | (ppm) | | | | | | | | | |
| Foliage | 9,770* | 12,800 | 1,090* | 1,200 | 4,070 | 4,020 | 3,060* | 3,350 | 940* | 812 |
| Live branch | 3,320* | 4,360 | 476* | 534 | 1,910* | 2,280 | 3,280* | 2,060 | 615* | 538 |
| Dead branch | 1,960* | 2,360 | 96* | 118 | 273 | 249 | 3,150* | 1,720 | 331* | 222 |
| Bole bark | 2,930 | 3,010 | 399* | 287 | 1,290* | 1,100 | 4,830* | 4,390 | 581* | 424 |
| Bole wood | 856* | 786 | 80* | 58 | 445 | 430 | 825* | 710 | 192* | 162 |

*Significantly different from jack pine at the 5 percent confidence level.

ly by its greater biomass and partly by its generally higher tissue nutrient concentration (table 3). Red pine nutrient concentrations of Ca and Mg are significantly higher than jack pine Ca and Mg concentrations for most tissues (table 3). For N and P, red pine concentrations are significantly higher or equal to jack pine concentrations in bole bark and bole wood, but lower in other tissues. Tissue K differed only slightly for red and jack pine.

By the age it is likely to be harvested, red pine will have produced significantly more biomass than jack pine, and will have accumulated even more of some nutrients, particularly P, Ca, and Mg. If nutrient removal by whole-tree harvesting is of concern, substantially fewer nutrients would be removed by leaving the crown on the site. In our study, we found that 36 to 64 percent of total above-ground nutrients are contained in the crown (foliage, live branches, and dead branches) (table 4). Harvesting in which the crown is left on the site will thus remove fewer nutrients, and with little reduction in yield because only 22 to 23 percent of the biomass is in the crown (table 4). For both species, bole-only harvesting will result in about a 50 percent reduction in nutrient removals from a site.

Table 4.—*Percent of total above-ground tree biomass and nutrients contained in the crown (foliage + live branches + dead branches)*

| | Red pine | | Jack pine | |
|---|---|---|---|---|
| | Mean percent in the crown | Standard deviation | Mean percent in the crown | Standard deviation |
| Biomass | 22 | 6.5 | 23 | 7.6 |
| N | 58 | 7.1 | 60 | 8.6 |
| P | 61 | 6.9 | 64 | 7.6 |
| K | 55 | 6.0 | 53 | 8.6 |
| Ca | 42 | 9.0 | 36 | 8.9 |
| Mg | 45 | 8.5 | 43 | 9.0 |

## Estimation of Accumulation

For most accurate results, nutrient accumulation on a specific site should be determined by felling trees, determining biomass, analyzing tree tissues for nutrients, and regressing nutrient contents against easily measured tree variables, such as d.b.h. and height. Such a costly, time-consuming procedure is seldom done.

An alternative approach presented here is to relate nutrient accumulation to easily measured stand variables, such as basal area and height. That such an approach might work is suggested by earlier studies that showed that volume (Buckman 1961) and biomass (Alban and Laidly 1982) were closely related to stand B and H for red and jack pine. For such an approach to work well for nutrients, the nutrient concentrations in a given tissue must not vary greatly from site to site in comparison with the variation in tissue biomass. That a species tissue nutrient concentration might not vary greatly seems reasonable because most nutrients are not limiting on most sites, and if a nutrient is not limiting, its concentration in a given tissue is largely genetically controlled. As an example, red pine bolewood biomass in the 24 stands of this study varied by a factor of 9 (25 to 228 t/ha), whereas N concentration in the same tissue varied by only a factor of 2 (667 to 1,125 ppm).

In the current study, good estimates (based on $R^2$ and the standard error of the mean) of biomass and macronutrient content accumulation can be made from stand basal area and height (table 5). For biomass, both B and H are necessary; for the nutrient contents, addition of H to the model with B does not improve the fit of the models. In either case, addition of variables for stand age, site index, or crown ratio does not materially improve the quality of fit. Biomass in these models is estimated with $Sy \cdot x / \bar{y}$ of 5 to 6 percent, and nutrient contents are about twice as variable.

Table 5.—*Models for estimating stand biomass and nutrient weights in total above-ground tree*[1]

| | a | b | $R^2$ | Sy • x | Sy • x/$\bar{y}$ |
|---|---|---|---|---|---|
| **RED PINE** | | | | | |
| Biomass[1] | 0.676 | 0.874 | 0.98 | 8.04 | 0.05 |
| Nitrogen[1] | 1.779 | 1.026 | .85 | 32.15 | .11 |
| Phosphorus | .439 | 1.030 | .80 | 4.31 | .14 |
| Potassium | 1.127 | .991 | .79 | 17.48 | .13 |
| Calcium | .348 | 1.355 | .91 | 26.38 | .11 |
| Magnesium | 1.246 | 1.350 | .91 | 5.49 | .12 |
| **JACK PINE** | | | | | |
| Biomass | 0.015 | 0.783 | 0.97 | 6.90 | 0.06 |
| Nitrogen | 2.934 | .751 | .74 | 22.07 | .10 |
| Phosphorus | .330 | 1.006 | .67 | 3.26 | .16 |
| Potassium | 1.326 | .966 | .75 | 11.25 | .12 |
| Calcium | 1.789 | .976 | .83 | 14.58 | .09 |
| Magnesium | 1.341 | 1.417 | .92 | 2.59 | .09 |

[1]For biomass the model form is $\ln(Y) = a + b \ln(X)$, where Y is biomass in tons/ha, and X is B • H where B is stand basal area in $m^2$/ha and H is height of dominant and codominant trees in m. For nutrients the model form is $\ln(Y) = a + b \ln(X)$ where Y is nutrient content in kg/ha, and X is basal area in $M^2$/ha.

Table 6.—*Models for estimating percentage of total tree biomass and nutrients in the crown (foliage + live branches + dead branches)*[1]

| | a | b | $R^2$ | Sy • x | Sy • x/$\bar{y}$ |
|---|---|---|---|---|---|
| **RED PINE** | | | | | |
| Biomass[1] | 99.0 | −12.03 | 0.78 | 3.07 | 0.14 |
| Nitrogen[1] | 142.3 | −13.09 | .75 | 3.68 | .06 |
| Phosphorus | 140.0 | −1.030 | .75 | 3.70 | .06 |
| Potassium | 115.8 | −9.44 | .55 | 4.12 | .07 |
| Calcium | 127.7 | −13.42 | .51 | 6.44 | .15 |
| Magnesium | 141.0 | −15.04 | .70 | 4.75 | .11 |
| **JACK PINE** | | | | | |
| Biomass | 111.6 | −14.84 | 0.68 | 4.42 | 0.20 |
| Nitrogen | 161.5 | −16.85 | .67 | 5.09 | .08 |
| Phosphorus | 157.7 | −15.41 | .72 | 4.14 | .06 |
| Potassium | 160.7 | −17.86 | .75 | 4.41 | .08 |
| Calcium | 141.9 | −17.55 | .68 | 5.17 | .14 |
| Magnesium | 152.4 | −18.27 | .73 | 4.82 | .11 |

[1]Model form:

$$Y = a + b \ln(X)$$

where Y is the percent of biomass or nutrients in the crown, and X = basal area ($m^2$/ha) times height (m).

Total stand tree biomass estimated from the model in table 5 agrees very closely (nearly always within 5 percent) with values obtained from equations developed earlier (Alban and Laidly 1982). In that study, more stands were sampled because the restriction of adjacent plantations was not necessary. That study should be consulted for equations useful in calculating stand biomass by tree tissue components as a function of stand basal area and height.

The proportion of biomass and nutrients in the crown is also a function of stand B and H and can be estimated from the models in table 6. Models in tables 5 and 6 should be applicable to typical unthinned red and jack pine plantations from ages 20 to 50 throughout the upper Great Lakes region.

The restriction of no thinning should be no problem for jack pine, which is seldom thinned, and no problem for red pine grown on short rotation for maximum fiber; but for red pine grown on longer rotations, thinning is a common practice that typically first occurs at ages 25 to 35. The models in table 5 should be applicable up to the first thinning, but beyond that time, insufficient data exist to ge certain of the effects on nutrient accumulation. Thinning will certainly increase the size of a tree's crown (Stiell 1966), but it will also increase the tree's diameter so that the ratio of crown weight to total tree weight might not change greatly. For example, Bockheim *et al.* (1986) measured biomass 7 years after thinning in a 37-year-old red pine plantation in Wisconsin (crown weight was 26 percent of total above-ground tree), identical to the value calculated from the models in table 6. For a 52-year-old Minnesota red pine plantation thinned 12 years previously, we measured the crown weight to be 19 percent of total tree weight. For this stand, the crown proportion from table 6 was 21 percent. Thus, from an admittedly small sample, there is little evidence to indicate major changes in the proportion of crown weight for red pine. If thinning does not affect the nutrient concentration of the tissues, then the models of tables 5 and 6 may be applicable (with caution) to thinned stands also. Clearly, studies are needed to establish the effects of thinning on biomass and nutrient distribution in red pine plantations.

If the tissue nutrient concentrations for a given stand differ substantially from those in table 3, large errors may result in nutrient estimates based on the models in table 5. Such might be the case, for example, in areas known to be severely deficient in one or more nutrients. In that case, one way to derive nutrient content estimates short of a full scale biomass and nutrient inventory would be to use the nutrient concentrations determined for that site combined with generalized biomass estimates

for each tissue based on basal area and height, which have been reported and verified previously (Alban and Laidly 1982). This approach was used successfully for jack pine by Green and Grigal (1980) in an area known to be low in phosphorus availability.

In addition to predicting nutrient accumulation for specific forest stands, the models presented here could also have more general application. For example, much of the growth information in the manager's handbooks for red and jack pine (Benzie 1977a,b) is presented in terms of basal area and height. Table 4 in the jack pine manager's handbook gives volume as a function of stand density (B), tree height (H), site index, and age. The models in table 5 of the current study could be used in conjunction with table 4 of the manager's handbook to estimate the effects of stand age and site index on nutrient accumulations.

## LITERATURE CITED


Alban, D. H. 1978. Growth of adjacent red and jack pine plantations in the Lake States. Journal of Forestry. 77: 418-421.

Alban, David H. 1985. Volume comparison of pine, spruce, and aspen growing side by side. Res. Note NC-327. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 6 p.

Alban, David H.; Laidly, Paul R. 1982. Generalized biomass equations for jack and red pine in the Lake States. Canadian Journal of Forest Research. 12: 913-921.

Baskerville, G. L. 1972. Use of logarithmic regressions in the estimation of plant biomass. Canadian Journal of Forest Research. 2: 49-53.

Benzie, John W. 1977a. Manager's handbook for jack pine in the north central States. Gen. Tech. Rep. NC-32. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 18 p.

Benzie, John W. 1977b. Manager's handbook for red pine in the north central States. Gen. Tech. Rep. NC-33. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 22 p.

Bockheim, J. G.; Leide, J. E.; Tavella, D. S. 1986. Distribution and cycling of macronutrients in a *Pinus resinosa* plantation fertilized with nitrogen and potassium. Canadian Journal of Forest Research. 16: 778-785.

Buckman, R. E. 1961. Development and use of three stand volume equations for Minnesota. Journal of Forestry. 59: 573-575.

Foster, N. W.; Morrison, I. K. 1976. Distribution and cycling of nutrients in a natural *Pinus banksiana* ecosystem. Ecology. 57: 110-120.

Freedman, B. 1981. Intensive forest harvest: a review of nutrient budget considerations. Inf. Rep. M-X-121. Canada: Canadian Forest Service, Maritimes Forestry Research Centre. 78 p.

Gessel, S. P., ed. 1986. Forest site and productivity. Martinus Nijhoff Publishers. 270 p.

Green, D. C.; Grigal, D. F. 1980. Nutrient accumulation in jack pine stands on deep and shallow soils over bedrock. Forest Science. 26: 325-333.

Leaf, A. L., ed. 1979. Impact of intensive harvesting on forest nutrient cycling. In: Proceedings, Impact of intensive harvesting on forest nutrient cycling; 1979 August 13-16; Syracuse, NY. Syracuse, NY: State University of New York, College of Environmental Science and Forestry. 421 p.

Lundgren, A. L. 1981. The effect of initial number of trees per acre and thinning densities on timber yields from red pine plantation in the Lake States. Res. Pap. NC-193. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 25 p.

Lundgren, A. L. 1983. New site productivity estimates for red pine in the Lake States. Journal of Forestry. 82: 714-717.

Lundgren, Allen L.; Dolid, William A. 1970. Biological growth functions describe published site index curves for Lake States timber species. Res. Pap. NC-36. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 9 p.

Perala, D. A.; Alban, D. H. 1982. Biomass, nutrient distribution, and litterfall in *Populus*, *Pinus*, and *Picea* stands on two different soils in Minnesota. Plant-Soil. 64: 177-192.

Stiell, W. M. 1966. Red pine crown development in relation to spacing. Publ. 1145. Ottawa, Canada: Canadian Department of Forestry. 44 p.

Turvey, N. D. 1981. Productivity in perpetuity. In: Proceedings, Australian Forest Nutrition Workshop; 1981 August 10-14; Canberra, Australia. Canberra, Australia: CSIRO Division of Forest Research. 366 p.

Wittwer, R. F.; Leaf, A. L.; Bickelhaupt, D. H. 1975. Biomass and chemical composition of fertilized and/or irrigated *Pinus resinosa* Ait. plantations. Plant and Soil. 42: 629-651.


U.S. GOVERNMENT PRINTING OFFICE